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HEAT TRANSFER AND FLAMMABILITY OF FIBROUS MATERIALS

ROBERT M. STANTON, CAPTAIN, USAF

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HEAT TRANSFER AND FLAMMABILITY OF FIBROUS MATERIALS

ROBERT M. STANTON, CAPTAIN, USAF

FOREWORD

This report was prepared by Robert M. Stanton, Capt, USAF, of the Fibrous Materials Branch, Nonmetallic Materials Division, Air Force Materials Laboratory. The work was performed under Project No. 7320, "Fibrous Materials for Decelerators and Structures," Task No. 732002, "Fibrous Structural Materials," and was administered by the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

Fabrics evaluated in this report were selected for possible use in the specific area of military air crew protection. This evaluation should not reflect upon the use of these materials for industrial and consumer requirements for heat and/or fire resistance which are generally less severe.

This report covers work conducted from July 1968 to February 1970.

Any failure to meet the objectives of this study is no reflection on the commercial items discussed herein or on their manufacturers.

This technical report has been reviewed and is approved.

JACK H. ROSS, Chief
Fibrous Materials Branch
Nonmetallic Materials Division

ABSTRACT

The need for nonflammable fibrous materials intended for incorporation into life support systems for aircrew protection from fires along with the state-of-the-art of such materials is discussed. Fabrics are evaluated on the basis of heat transmission from direct flame contact as well as for flammability. Five characteristics have been found to affect fabric heat transfer: fiber thermal stability, thickness, weave or knit pattern, air permeability and bulk density. PBI is the only fiber in woven form that has provided the combined thermal and comfort characteristics required for use in flight suits.

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INTRODUCTION

Fire has been one of man's most formidable foes since the beginning of time. Fire often causes permanent damage to man rendering him incapable of living a normal existence or it has caused the direct loss of his life. One way of providing protection for him from thermal hazards is by means of protective wearing apparel. The United States Air Force is constantly looking for new and improved fibrous materials to fulfill the ever increasing needs of Air Force applications. High priority examples of the need for advanced nonflammable materials can be found in the potential fire hazards that exist in daily work tasks performed by Air Force personnel. Some of these examples are fuel handling, on the ground and in the air, providing a ready supply of ammunition for combat situations, and aircraft accidents involving fire. From the examples cited, fire is the most critical event in ground egress situations. Approximately 50% of the personnel involved in past ground egress accidents were exposed to fire, the major cause of the fatalities and injuries. (Reference 1).

Past efforts by the Air Force Materials Laboratory have resulted in a considerable amount of data dealing with the development of materials for personnel protection (References 2 to 9). This report deals with evaluation of new materials for use in wearing apparel exposed to direct flame contact. The operational requirements for personnel protection equipment and materials proposed are outlined in the System Package Program, for the Life Support System 412A (Reference 10).

The report deals with thermal characteristics of fabrics intended for use in wearing apparel, but this by no means is the total acceptance criteria. The comfort provided the wearer and the ability of the fiber type to be made into a durable garment that is pleasing to the eye are also factors of considerable importance.

A great deal of discussion has been created over the required protection for personnel from injury due to flames. An acceptance criteria that might be used could most definitely be based on protection time provided by the various fabrics against a certain degree of burn. The degree of protection aimed at is total protection from burns, but since no suitable materials exist that will provide complete protection, a more realistic level had to be chosen. That degree of damage that has been most widely used by investigators in the development of protective clothing items is the point where blistering occurs on the skin surface which is the interface between second and third degree burns.

Protection time (or escape time from a crash situation) has been set at various levels by the Army, Navy and Air Force. These times range from three to ten seconds. The Army's ten-second requirement is based on total escape time from exit of the burning vehicle to exit from the flame area. The Navy bases its three-second escape time on the theory that a man running could escape from a 30- to 50-foot radius of flame area if he was moving at 10 to just under 17 feet per second. This speed range is far below the actual speed that the average man is capable of because physiological effects of the thermal hazard are also used to determine the resultant time of three seconds. Various

organizations throughout the Air Force have cited protection times that fall within a three- to 10-second range.

Past in-house efforts have shown that the majority of single layer fabrics presently being used provide less than three seconds protection time. The author decided to use the three-second exposure level with the ultimate goal the 10- second exposure level as soon as it has been determined that fabrics exist that can provide greater than three seconds protection time. The above acceptance criteria, of necessity has to be based on user comfort, on his ability to perform functional and mission objectives and on acceptability to the user.

SECTION II

DISCUSSION

To be an effective thermal barrier to flames, a fabric must provide blockage of heat from convection, conduction and radiation. If we consider the case where the fabric is held firmly against the body (e.g., arm flexed, pulling fabric tightly against skin); this would represent the most vulnerable situation for the passage of heat through the fabric due to flames. Hot convective currents and radiant energy would penetrate the pore area of the fabric and the fabric acting as a conductor would also pass heat through to the skin.

To provide adequate thermal protection the fabric must not burn or melt. A fabric that does so will carry the flames with the victim once he has escaped from the fire. Thus, if we consider fabrics that will not support combustion or, will not burn in the presence of flame, the amount of protection is constituted by the following fiber characteristics: they must have a) thermal stability, b) blockage of convective and radiative heat, and c) low level heat conduction. It is obvious, in order to provide the latter two points, the fabric must remain intact throughout the length of the exposure or it must provide a substitute barrier by nature of its thermal degradation process.

A fabric can be considered as a composite, or a heterogeneous system made up of solid material (fiber) and air. The thermal conductivity of the constituent fibers range from 3 to 8 x 10^{-4} cal-cm/°C-cm^2-sec which is considerably higher than that of air (k_{air} = 0.57 x 10^{-4} cal-cm/°C-cm^2-sec).

It is also known that the thermal conductivity of most polymeric materials rises very rapidly compared to that of air when subjected to elevated temperatures. The fibers themselves then become the most hazardous component of the composite members.

Since a fabric is a porous material it allows radiant energy to pass through the pores and from the pores. It also permits hot convective currents to pass through to the skin. The ideal fabric would then be constituted by two layers of thin nonporous thermally stable materials separated by a stagnant air space or by some other material with a lower thermal conductivity than that of air. A fabric with these characteristics would be prohibitive for normal comfort and performance of mission objectives. Therefore, the most practical system would be a fabric with enough fiber present to prevent the conduction of heat and block convective and radiative heat as well.

Fabric bulk density is then a factor when considering the potential effectiveness of a fabric as a thermal barrier. Fabric bulk density is the average weight of solid material per unit volume of fabric. Bulk density can, however, be affected by many factors. If the fabric is made up of tight yarns due to high twist, it can present a relatively open or loosely woven fabric and still have the same bulk density of a closely woven fabric with low twist yarns. Variations in fiber densities can also affect the resultant fabric bulk density. The fabrics with the highest bulk density, or with the least amount of "trapped air", would constitute the best conductor of heat and would therefore be the least desirable for thermal protection.

Offsetting the advantage of decreasing the amount of the fiber per unit volume of fabric is the adverse effect on the blockage of convective and radiative heat. The fabric will allow more or less air flow, when subjected to a differential pressure, depending upon the density distribution of the fibers. Fabric air permeability may be used as a means of determining the degree of heat transfer affected by the fiber distribution throughout a given volume of fabric.

When discussing the general theory of heat transfer, distance is the dominating factor that affects all modes of heat transfer. In the present discussion this relates to fabric thickness. Increasing fabric thickness can offset the adverse effects of high fabric bulk density or high fabric air permeability. The resultant temperature rise on the back side of a fabric in direct flame contact can be related directly to alternations in fabric thickness. One of the objectives of this report will be to determine just how much fabric thickness is required to offset the adverse effects of high air permeability and high fabric density.

Fabric density, air permeability and thickness are all factors that are affected by the way the fabric is constructed (i.e., yarn number, yarns per inch, yarn twist, twist multiplier, weave pattern, etc.). Once it has been determined how the resultant characteristics affect heat transmission, the fabric construction can be altered to enhance its thermal protection capabilities.

The remaining factor to be discussed that can affect the heat blocking ability of a fabric is the nature of the constituent fibers. A fiber

that will melt or burn can carry the dangers of the fire with the escaping personnel who have fled the immediate hazard. A fiber that is not thermally stable to flames can break down causing the loss of the thermal barrier or it can allow the fabric to shrink and come into closer contact with the body setting up an efficient heat transfer system by eliminating the air space between the fabric and skin.

As determined by the above discussion this work was based on the premise that the characteristics that would bring about the thermal protection from flames provided by fabrics are as follows:

a. Fiber thermal stability,

b. Fabric thickness,

c. Fabric air permeability,

d. Fabric bulk density,

e. Fabric construction.

When these characteristics are combined with personnel comfort factors and mission objectives, a formidable task remains to find a material that will not inhibit or restrict the wearer's actions in the confined quarters of the aircraft cockpit.

SECTION III

MATERIALS EVALUATED

The fabrics included in this report represent Air Force inventory items and experimental fabrics from military and industrial sources. Both combustible and noncombustible fabrics have been included. A list of the fabric sources are given in Table I.

Several fabrics bear further comments. The modified aromatic polyamides are chemically and heat treated Nomex® fabrics. This process results in a more thermally stable fabric. Poly-1, 3, 4-benzimidazole (PBI) is an Air Force developed fiber scaled up to semi-pilot plane status under Contract AF33(657)-11232 with Celanese Research Corporation (Reference 11). Kynol is described by its producer as a phenolic fiber cross-linked in a novel manner to affect the fiber forming substance.

The individual fabrics evaluated and the construction of the same are shown in Table II. The fabrics represent a wide cross section of fabric constructions. Continuous filament yarns are denoted by an asterisk and they represent fabrics with the highest bulk densities.

The fabrics of Table III have been listed separately because they were used to determine the effects of the fabric construction characteristi on heat transmission. These fabrics were developed under Contract F33657-69-C-0256 with Fabric Research Laboratories, and are all woven from 1.5 denier per filament staple with varied yarn counts to effect the change

in the fabric construction. A 2/1 twill weave pattern was used for all of the PBI fabrics except for three 3/3 twill weave fabrics which have been designated in Table III.

TABLE I

FABRICS

GENERIC TYPE	SOURCE	TRADE NAME	LOG NO.
Cellulose	U.S.A.F. Inventory	Cotton (MIL-C-5039)	1
Treated Cellulose	U.S.A.F. Inventory	Fire Retardant Cotton (MIL-C-18387)	2
E-Composition glass beta diameter	Owens/ Corning Fiberglass	Beta® glass	3
Modified aromatic polyamide	David Clark Co. Inc.,	F-Fabric®	4
	Travis Mills Corp.	Fi-Pro®	5, 30, 31
	Monsanto	Durette®	11, 12, 32, 33, 34
Aromatic polyamide	E.I. duPont deNemours	Nomex®	6, 7, 13, 26, 28, 29, 39, 45
Poly-1,3,4-benzimidazole	U.S.A.F. experimental	PBI	8, 9, 27, 37, & Table III
Phenolic	Carborundum Company	Kynol®	10, 46, 47

® registered trade mark of specified company.

TABLE II

FABRIC CONSTRUCTION

Log. No.	Fiber Type	Weight $(oz/yd)^2$	Thickness (mils)	Weave or Knit Design	Yarns Per Inch	Fabric Density (g/cc)	Fiber Density (g/cc)
1	COTTON	5.0	13.1	2/1 twill	140x100	.50	1.54
2	FR COTTON	4.9	10.5	2/1 twill	108 x 96	.62	1.51
3	*β-GLASS	6.3	6.6	plain	72 x 60	1.27	2.59
4	*F-FABRIC	5.0	10.2	plain	66 x 50	.65	1.44
5	Fi-Pro	5.0	15.0	3/1 twill	95 x 76	.45	1.40
6	NOMEX	3.7	13.1	H.B. twill	108 x 74	.38	1.38
7	NOMEX	5.0	14.5	H.B. twill	94 x 68	.46	1.38
8	PBI	3.7	12.0	H.B. twill	112 x 76	.39	1.32
9	PBI	5.9	16.2	H.B. twill	96 x 76	.49	1.32
10	KYNOL	5.1	20.2	2/2 twill	47 x 42	.33	1.25
11	*DURETTE-Gold	6.0	12.4	plain	54 x 44	.65	1.43
12	*DURETTE-Black	5.8	12.1	plain	55 x 45	.64	1.41
13	NOMEX	7.0	24.2	tricot	--------	.39	1.38
26	NOMEX	4.2	12.7	2/2 twill	124 x 94	.45	1.38
27	PBI	4.8	28.5	1 x 1 rib	--------	.22	1.32
28	*NOMEX	5.0	11.0	2/1 twill	96 x 57	.63	1.38
29	NOMEX	6.1	16.0	2/2 twill	72 x 61	.52	1.38
30	FIPRO	6.0	15.5	2/2 twill	72 x 61	.52	1.40
31	*FIPRO	5.3	11.0	2/1 twill	96 x 57	.65	1.40
32	DURETTE-Gold	5.0	16.0	3/1 twill	96 x 72	.42	1.43
33	DURETTE-Gold	4.7	14.9	plain	52 x 40	.42	1.43
34	DURETTE-Gold	3.9	10.5	plain (modified)	80 x 80	.49	1.43
39	NOMEX	7.0	35.6	thermal	--------	.26	1.38
45	NOMEX	6.1	30.5	plain (bi-ply)	--------	.27	1.38
46	KYNOL	4.3	22.0	plain **	42 x 32	.26	1.25
47	KYNOL	5.2	24.0	2/1 twill	57 x 44	.29	1.25

*Continuous filament yarns

** bi-ply - Two plain knit fabrics bonded by intermittent stitching.

TABLE III

PBI FABRICS (1.5 dpf)

Log No.	Thickness (mils)	Weight (oz/yd^2)	Ends x Picks Per Inch	Weave	Fabric Density (g/cc)	Air Permeability ($ft^3/ft^2/min$)
14	7.6	2.9	118 x 91	2/1twill	.50	61
15	10.3	3.0	115 x 116	2/1 "	.38	96
16	12.4	4.9	92 x 85	3/3 "	.52	17
17	12.7	3.6	90 x 92	2/1 "	.37	121
18	12.7	3.4	89 x 90	2/1 "	.35	74
19	13.2	4.2	80 x 81	2/1 "	.42	48
20	15.5	4.6	91 x 83	3/3 "	.39	70
21	15.0	4.4	82 x 84	2/1 "	.39	99
22	16.3	5.4	70 x 84	2/1 "	.44	64
23	18.0	6.2	76 x 65	2/1 "	.46	32
24	19.5	6.7	59 x 60	2/1 "	.46	49
25	24.5	8.3	81 x 78	3/3 "	.45	16
35	11.5	4.7	71 x 65	2/1 "	.54	29
36	15.4	6.2	63 x 60	2/1 "	.53	29

SECTION IV

TEST PROCEDURES

The evaluation procedures used to determine the various fabric properties have been described in the Federal Test Method Standard No. 191. The flammability data was obtained through the standard "Flame resistance of cloth, vertical method" No. 5903, and by surface exposure of fabrics to flames in a horizontal plane. The test procedure for heat transfer through fabrics upon direct flame contact was developed by the Naval Air Development Center and has been described at length in the literature, (References 12 and 13).

The heat transfer apparatus (Figure 1) was fabricated in the laboratory by mounting a shutter device (B) in a horizontal table-like structure. A brass cover plate (C) was provided to protect the lucite mounting block which houses the skin simulant material (F). The brass cover plate has a one and three eighths inch diameter aperture and is formed to fit the two-inch radius of curvature of the Naval Material Laboratory (NML) skin simulant.

The NML skin simulant has been described in detail by Derksen et. al. (References 14 and 15). Briefly, the simulant is made from a mixture of alpha cellulose, urea formaldehyde with silica powder filler. A two-mil copper-constantan thermocouple (G) (Figure 1) with the wire in the vicinity of the junction point pressed flat to an effective thickness of 0.001 cm. is imbedded at a depth of 0.05 cm from the curved surface of the NML skin simulant.

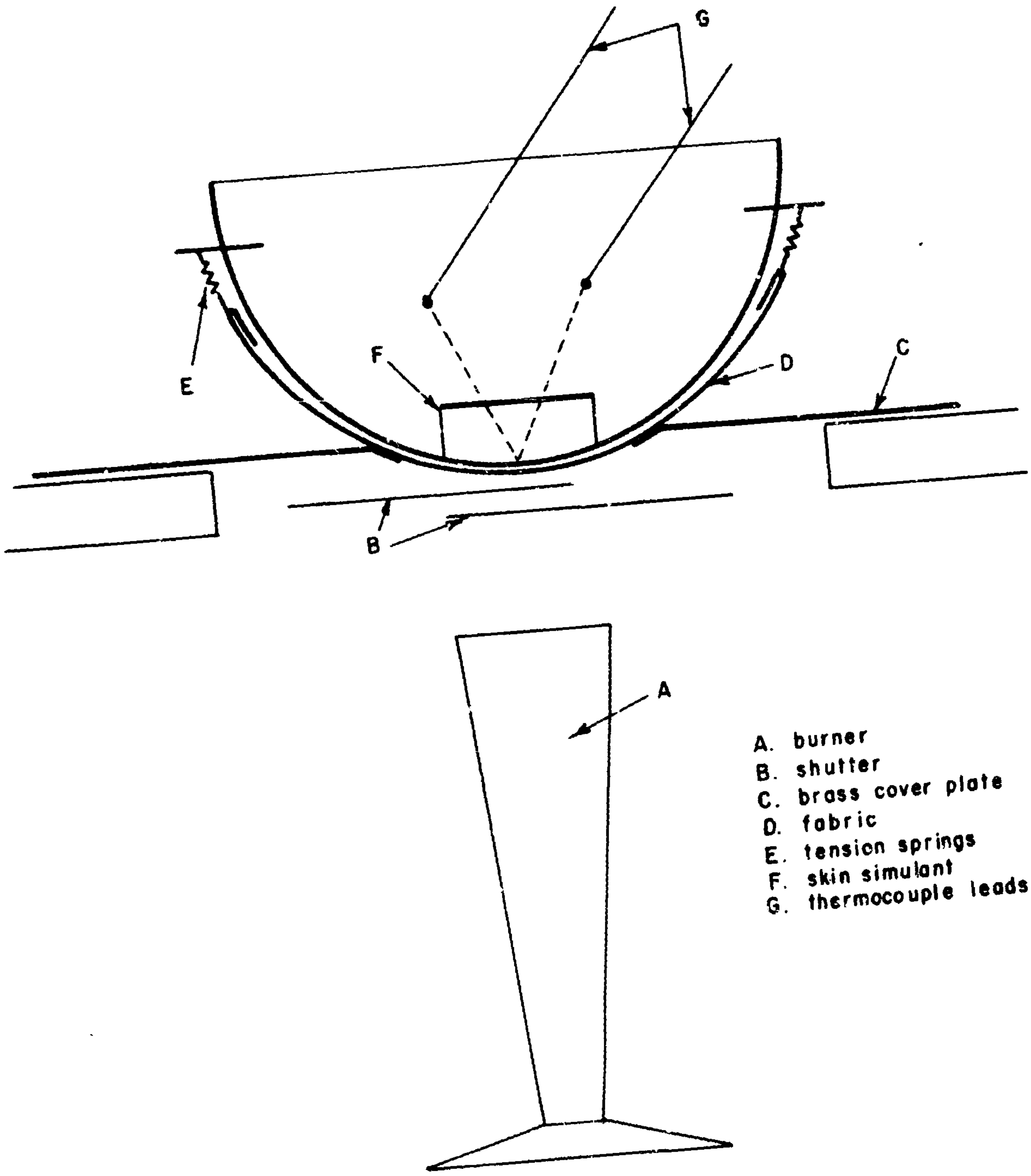


Figure 1. Heat Transfer Apparatus Schematic

The flame source is provided by a Fisher burner (A), natural gas model (No. 3-902), and is fed with natural gas through a calibrated flowmeter at a rate of two liters per minute. The flame temperature as measured by a two-mil type R thermocouple, is 1372°C and when impinged on the bare NML skin simulant, the average resultant energy absorbed is 1.3 cal/cm^2-sec.

Since the energy absorbed as a result of the flame contact varies from 1.27 to 1.32 cal/cm^2-sec, it is necessary to equilibrate mathematically the exposure level from run to run. As described by Stoll, et. al. (Reference 13) the absorbed energy may be found by dividing the temperature rise of the bare NML skin simulant upon direct flame contact, by 36.2°C, the temperature rise corresponding to an energy absorption level of one cal/cm^2-sec by the bare simulant. Then by dividing the temperature rise of each fabric-covered simulant exposure by the resultant energy level for each test the temperature rise for the equivalent energy absorption level of one cal/cm^2-sec can be determined (Figure 2). The calculated protection time against blistering (PAB) is also based on work by Stoll, et. al. (Reference 13). Corresponding temperature rise versus protection times have been plotted by Stoll based on extensive burn data from both animal and human skin burns. Since it was determined that the energy absorption level was fairly consistent in adjacent runs, with the proper control of gas flow and flame configuration, runs were alternated by first exposing the bare simulant and then the fabric-covered simulant and so on until five fabrics of each material were exposed. Reproducibility attained in the resultant data from run to run was highly consistent in this manner as opposed to monitoring the flame temperature during each

$$^{*}H = \frac{T_{bss}}{36.2^\circ C}$$

$$T_{ss} = \frac{T_{css}}{H}$$

Where:

T_{bss}	= Temperature rise of bare skin simulant
T_{css}	= Temperature rise of fabric covered skin simulant
T_{ss}	= Temperature rise of fabric covered skin simulant at an equivalent energy absorption level of 1 cal/cm^2-sec
H	= Heat flux absorption level perpendicular to skin simulant surface
36.2°C	= Temperature rise equivalent to an energy absorption level of 1 cal/cm^2-sec as received by the bare simulant upon direct flame contact

*Based on three seconds exposure time.

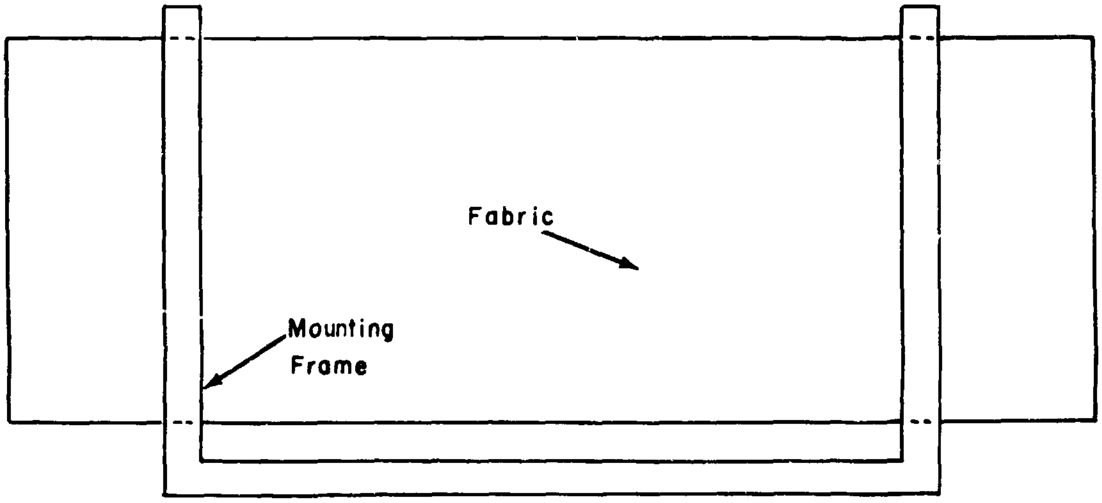
Figure 2. Sample Calculations

run. It must be understood that the condition created in the laboratory testing is as severe a condition that could exist in an aircraft fire for the same exposure time. Fabrics during testing are under tension causing them to come in close contact with the skin which places them in the most vulnerable situation for passage of heat due to flames. The flame temperature for the laboratory testing is 1372°C which is higher than the average flame temperature of 1000°C for JP-4 fuel fires. The energy source is in the form of an undisturbed rectangular pulse while

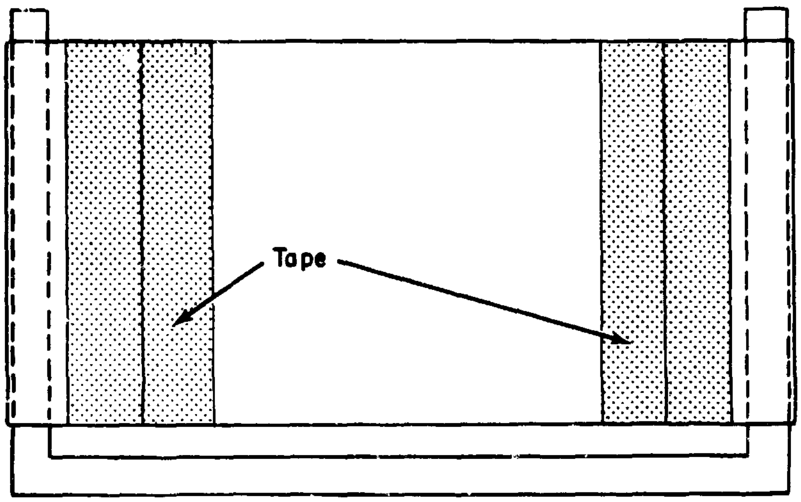
in an actual fire the subject might be exposed to a wavering pulse of high and low energy output levels. Most assuredly the data analysis was originally designed on the safe side when determining the PAB for each fabric evaluated.

Two differences exist in the described testing procedures as compared to the work by Stoll. In Stoll's testing procedures, she does not apply tension to the fabrics and the flame temperature for each individual run is monitored.

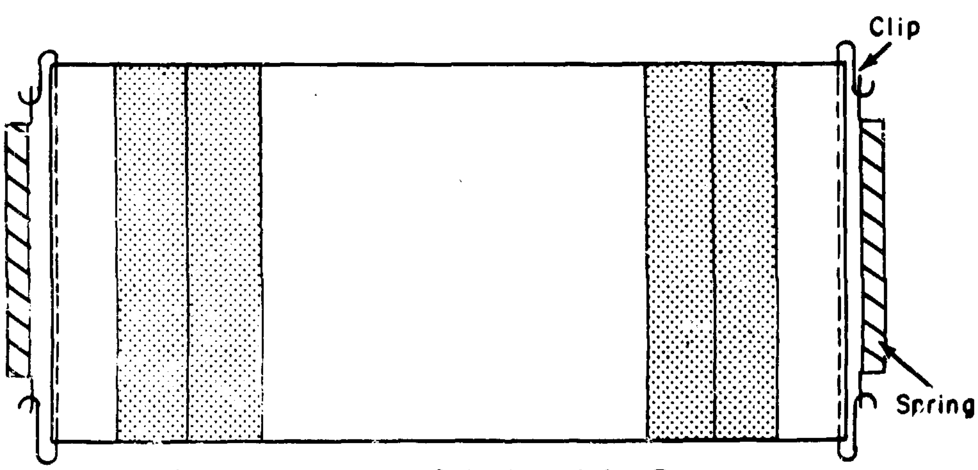
The fabric mounting technique (Figure 3) was designed to assure the same set of conditions for each fabric tested. By tensioning the fabric at the same level for each test by means of springs, the air space between the fabric and the simulant was determined by the fabric construction as would be seen in a real situation. This mounting procedure was used instead of over-laying the fabric on the simulant under no set tension, as is done by the Naval Air Development Center. The amount of tension used was set at 150 grams and with a two-inch wide sample this amounted to 75 grams per inch of fabric width. The tension was enough to hold the fabric firmly but was not so high that it would distort the fabric. All fabrics were mounted by cutting the longest side in the direction of the warp and using a 6 in. x 2 in. sample size. The samples were fastened on a mounting frame to provide a consistent length from sample to sample. The fabric was taped back over itself to provide loops to insert the spring clips. The knit fabrics had to be mounted in a different manner



A. Mounting Frame Over Fabric



B. Fabric Edges Taped In Position



C. Springs and Clips Substituted for Frame

Figure 3. Sample Mounting Technique

because the tension was high enough to distort them. These samples were mounted with 20 grams of tension to maintain fabric contact with the NML simulant. The position of the sample surface was 1 1/16 inches above the burner surface.

The test was conducted by positioning the burner under the simulant which by means of a micro switch simultaneously started the recorder, and timer and opened the shutter. Photographs of the heat transfer apparatus are provided in Figures 4 and 5.

During the heat transfer studies the fabrics were exposed to flame impingement with the aid of a heat sink on the back side of the fabric. The absorption of the heat by the simulant allowed the fabric to remain undamaged, or at least it prevented the fabric from experiencing the full amount of energy delivered by the fire. In order to evaluate the effect of surface impingement of flames as would be seen in the areas where the fabric was held loosely on the wearer, the following test was initiated. The heat transfer table previously described was used with the skin simulant removed from the table as well as the brass cover plate. The fabrics were taped to a steel plate with a three-inch diameter circular aperture to allow flame impingement on the fabric surface. The exposure time was three seconds, and visual observations during and after the test, were made, to determine the effects on the surface by direct flame contact.

Figure 4. Heat Transfer Apparatus

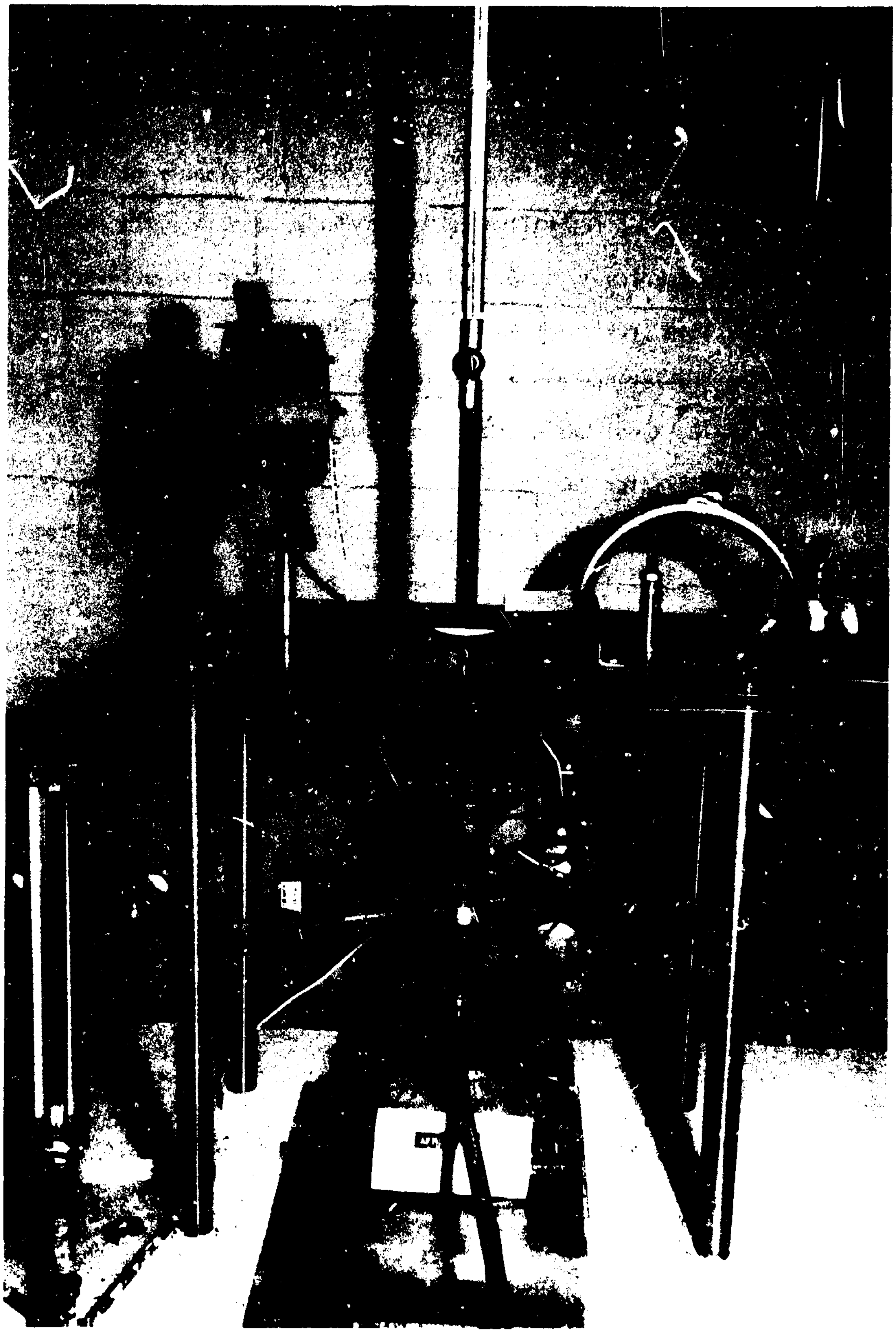


Figure 5. Heat Transfer Apparatus

SECTION V

RESULTS

Mechanical properties of the fabrics (Table IV) have clearly demonstrated that the new generation of thermally stable polymeric materials (those materials excluding fabrics 1, 2, 3, and 10) should all provide greater fabric durability than previously used cotton. The new fabrics have improved abrasion resistance as well as improved tearing and breaking strength. Fabric 10, Kynoi has not been developed to the point where it can be evaluated fairly for fabric durability. Kynol has been included only because of its ability to resist flames and will have to be evaluated further once its mechanical properties have been optimized.

Comfort aspects of wearing apparel can be related to the ability of the fabric to transmit moisture. Percent moisture regain is used to predict the comfort provided a wearer. Cotton, because of the high degree of comfort that it offers, is used as a control. The percent moisture regain of the fabrics (Table IV) demonstrate that only PBI has a moisture regain that should provide equal or better comfort when compared to that of cotton. The 11 to 12% moisture regain quoted for PBI is just slightly higher than the 10% generally quoted for cotton.

The above discussion is a brief encounter of the additional aspects that must be considered for the acceptance of a fabric for use in wearing apparel. These laboratory evaluations are used as indicators to determine which materials should undergo the final and most critical evaluation, that of an actual wear test by Air Force personnel.

TABLE IV

FABRIC PROPERTIES

Log No.	Fiber Type	Moisture Regain (%)*	Air Permeability ($ft^3/ft^2/min$)	**Abrasion Resistance		Breaking Strength and Elongation		Tearing Strength	
				Taber	Schiefer	Warp	Fill	Warp	Fill
				(cycles)		(lbs/% elongation)		(lbs)	
1	Cotton	10	53	87	29	124/6	45/15	3.3	2.7
2	FR Cotton	7	65	113	35	99/6	57/12	12.9	7.5
3	Beta Glass	--	3	---	---	125/9	127/4	5.1	5.5
4	F-Fabric	7	9	112	219	122/21	113/15	5.9	5.3
5	Fi-Pro	5	143	165	91	------	------	----	----
6	Nomex	5	244	372	118	108/40	65/27	24.8	16.7
7	Nomex	4	164	244	191	131/34	72/26	23.1	16.9
8	PBI	11	168	291	103	84/19	54/14	13.6	9.3
9	PBI	12	53	588	205	121/29	96/23	14.9	12.0
10	Kynol	5	153	75	50	33/9	29/9	8.8	8.9
11	Durette-Gold	4	30	239	210	143/29	124/31	9.3	8.5
12	Durette-Blk.	4	42	159	100	159/18	119/16	11.3	9.2
13	Nomex	--	339	590	---	171/69	139/86	18.9	16.1
26	Nomex	--	113	180	---	119/34	80/29	13.5	11.0

* Moisture regain measured at 65% R.H. and 70°F

** Schiefer: No. 3 emery abradent used,

Taber: Wheel No. CS-17

Two up, one down, twill weave, PBI fabrics (Figures 6 and 7) were used to determine the effect of fabric thickness on heat block capability. Also, the availability of the PBI fabrics in a wide range of fabric constructions dictated its use for determining the effects of fabric construction. PBI fabrics used for this purpose are listed in Table III. A best fit straight line has been provided for Figures 6 and 7 while the plot of Figure 8 is an extension of the equation for the straight line as determined by the discussed series of PBI fabrics. The data points for Figures 6, 7, and 8 are temperature rise versus fabric thickness as determined by the temperature rise of the NML skin simulant. The temperature rise is for an absorption level of one cal/cm^2-sec that would be absorbed by the bare skin simulant upon direct flame contact ($H = \Delta T_{css}/36.2°C$). This method is used, as suggested by Stoll (Reference 13) so that the data reported can be compared to data from other laboratories using the same procedure.

The variance of the data points from the PBI control is caused, in part, by the deviations in the construction of the various fabrics. High fabric air permeability has been shown to adversely affect heat transmission. High yarn twist and low ends and picks per inch result in poor fabric cover and the air is allowed to move freely through the fabric. This effect has only been seen to be true with those fabrics exhibiting a thickness in the normal flight suit fabric range (10 to 16 mils) and in woven form. The knit fabrics of high thickness and high air permeability still provide good thermal protection because the adverse high air permeability is offset by the high fabric thickness and the low fabric density.

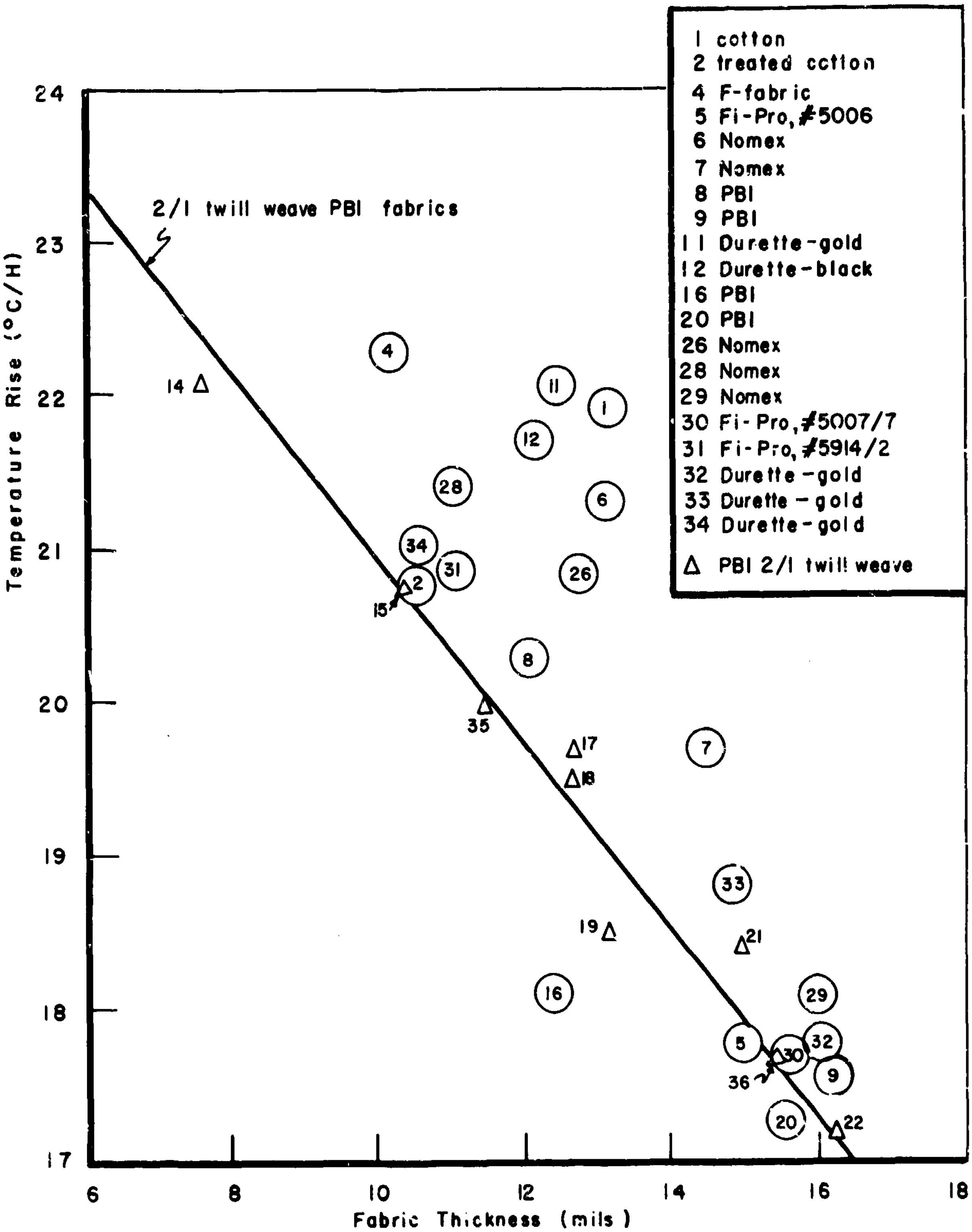


Figure 6. Temperature Rise vs Fabric Thickness

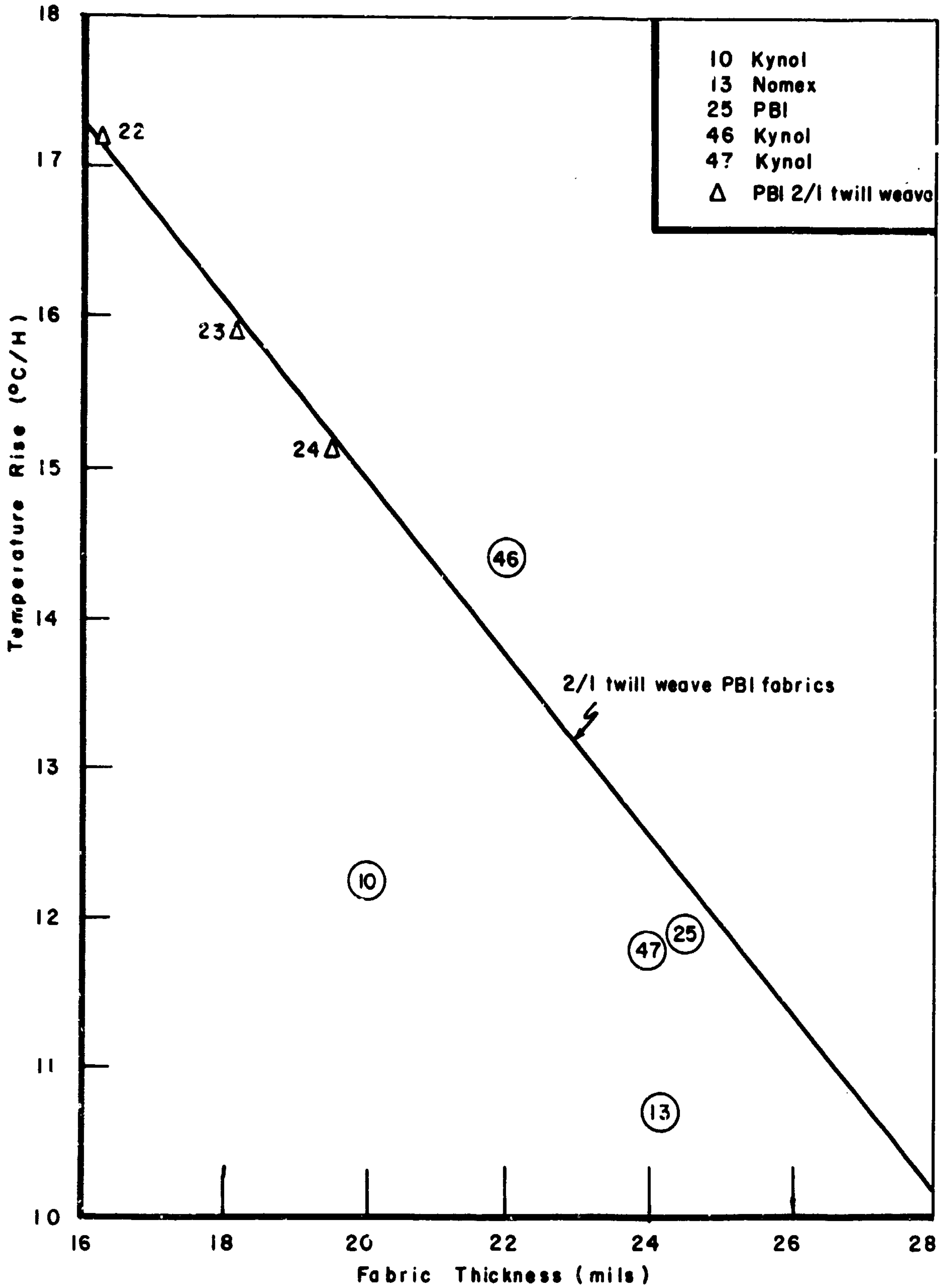


Figure 7. Temperature Rise vs Fabric Thickness

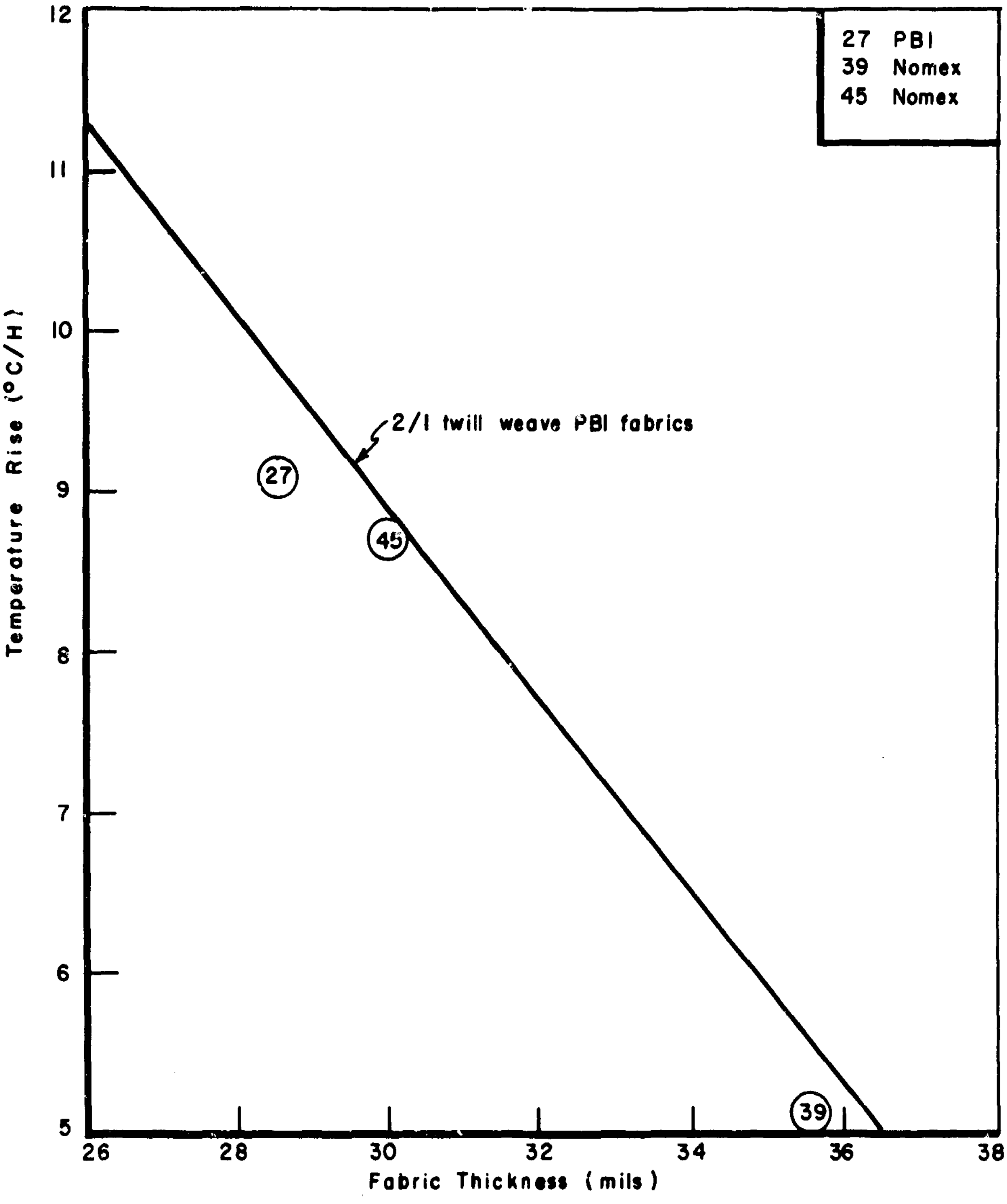


Figure 8. Temperature Rise vs Fabric Thickness

Fabric density had little or no effect on heat transmission when it was within the normal range of woven staple fabrics (0.38 to 0.52 g/cc). When the fabric density was increased to (0.59 to 0.65 g/cc), the rate of heat transmission increased. This can be seen clearly by examining the continuous versus staple Durette-gold fabrics. The low density fabrics (0.22 to 0.39 g/cc) can only effect good heat blockage when they are of sufficient thickness to still provide good fabric cover.

Weave pattern can be used effectively to increase thermal protection. 3/3 twill weave PBI fabrics (Log Nos. 16, 20, and 25, Table V) have fewer interlacings from face to back of the fabric and thus present fewer direct paths for passage of heat. The plain weave fabrics are the poorest for thermal protection purposes. Kynol fabrics were evaluated with three different weave patterns (fabrics 10, 46, and 47) with results as shown in Figure 6. As the percentage of warp or fill yarns is increased on the face of the fabric, the degree of thermal insulation increases for a short response time with high temperature exposure.

The limiting factor for changing the weave pattern to the more effective twills is the resultant adverse mechanical characteristics of the fabrics. Increasing the percent of warp or fill yarns on the face of the fabric decreases the fabric's dimensional stability or causes the fabric to become sleazy and less abrasion resistant. The weave pattern must then be chosen with many parameters in mind and as shown above the choice should include the effect of weave pattern on thermal insulation.

TABLE V

PROTECTION PROVIDED BY FABRICS

LOG NO.	FIBER TYPE	THICKNESS (MILS)	ΔT_{css} at 1.3 cal/ cm^2-sec(°C)	PAB (SEC)	ΔT_{css} (°C/H)	PAB (SEC)
1	cotton	13.1	28.5	1.8	21.9	2.6
2	Hooker cotton	10.5	27.0	2.0	20.8	2.8
3	*Beta-glass	6.6	38.4	1.2	29.5	1.7
4	*F-Fabric	10.2	29.0	1.8	22.3	2.5
5	Fi-Pro	15.0	23.1	2.4	17.8	3.5
6	Nomex	13.1	27.7	1.9	21.3	2.7
7	Nomex	14.5	25.6	2.1	19.7	3.0
8	PBI	12.0	26.4	2.0	20.3	2.9
9	PBI	16.2	22.9	2.5	17.6	3.6
10	Kynol	20.0	16.3	4.0	12.5	5.8
11	*Durette-gold	12.4	28.7	1.8	22.1	2.6
12	*Durette-black	12.1	28.2	1.8	21.7	2.6
13	Nomex	24.2	13.9	5.5	10.7	7.2
14	PBI	7.6	28.7	1.8	22.1	2.6
15	PBI	10.3	26.9	2.0	20.7	2.8
16	PBI	12.4	23.5	2.4	18.1	3.4
17	PBI	12.7	25.6	2.1	19.7	3.1
18	PBI	12.7	25.4	2.1	19.5	3.1
19	PBI	13.2	24.1	2.3	18.5	3.3
20	PBI	15.5	22.5	2.5	17.3	3.6
21	PBI	15.0	23.9	2.3	18.4	3.4
22	PBI	16.3	22.4	2.5	17.2	3.7
23	PBI	18.0	20.0	3.0	15.9	4.2
24	PBI	19.5	19.6	3.0	15.1	4.4
25	PBI	24.5	15.4	4.3	11.9	6.1
26	Nomex	12.7	27.2	1.9	20.9	2.8
27	PBI	28.5	11.8	6.3	9.1	9.1
28	*Nomex	11.0	27.8	1.9	21.4	2.7
29	Nomex	16.0	23.5	2.4	18.1	3.4
30	Fi-Pro	15.5	22.2	2.6	17.7	3.5
31	*Fi-Pro	11.0	26.7	2.0	20.0	2.8
32	Durette-gold	16.0	23.1	2.4	17.8	3.5
33	Durette-gold	14.9	24.4	2.3	18.8	3.3
34	Durette-gold	10.5	27.3	1.9	21.0	2.8
35	PBI	11.5	26.0	2.1	20.0	3.0
36	PBI	15.4	23.0	2.4	17.7	3.5
39	Nomex	35.6	6.6	14.0	5.1	20.0
45	Nomex	30.5	11.3	6.0	8.7	9.6
46	Kynol	22.0	18.7	3.3	14.4	4.7
47	Kynol	24.0	15.3	4.4	11.8	6.4

*Continuous Filament Yarns

All of the PBI fabrics, excluding fabrics 8 and 9 are woven from yarns of 1.5 dpf staple fibers. Yarns in fabrics 8 and 9 are from 2.0 dpf staple fibers. The decrease in filament size was expected to allow better cover because these fabrics constitute a more homogenecus mixture of fiber and air. Although a slight difference in heat block capability did result, the difference was not significant.

The effect of fiber thermal conductivity is demonstrated vividly by the glass fabric. The Beta-glass fabric (Fabric 3) showed a resultant temperature rise of 29.5°C at 1 cal/cm^2-sec for 6.6 mils of fabric thickness; this represents a high rate of heat passage. The thermal conductivity of the remaining fiber types are all similar if we consider heat transmission of each. Cotton and Nomex fabrics provided less protection than the PBI fabrics. This is an effect of poor fiber thermal stability or of high fiber thermal conductivity. It is difficult to determine the fiber thermal conductivity because of the dissimilarities that exist in the construction of each fabric. The data indicated more of an effect of fabric thermal conductivity than fiber thermal conductivity.

The knit fabrics show excellent potential for fire protection. The three-second temperature rise for the knit fabrics can be found in Figures 7 and 8. The line for the 2/1 twill weave PBI fabrics has been extended beyond its data point in Figure 7 and also into Figure 8 to provide a basis for comparison for 20- to 30-mil fabric thicknesses. Woven fabrics in the same thickness range as the knit fabrics were not available for evaluation and in all likelihood would have been too heavy for wearing apparel. While knit fabrics are made for high air permeability

for comfort, they are thicker but lower in weight. Since thickness is the dominating factor for heat transmission, the knit fabrics with their ability to trap a large quantity of air with low fiber mass make effective thermal barriers. The actual resultant heat transmission for an equivalent thickness of woven staple fabrics might not fall on the extrapolated curve, but in fact it might be as good as the knit fabrics. The problem here would be prohibitive fabric weight to effect the same heat transmission as the knit fabrics.

The fabrics constructed from continuous filament yarns have all demonstrated a higher rate of heat passage than the staple fabrics. The best example of this point is the Durette-gold fabrics which were supplied in both continuous filament and staple form. The continuous filament fabrics provide a continuous path from face to back of the fabric and present a much denser structure, or more fiber than air, per unit volume of fabric when compared to the staple fabrics. The Durette staple fabrics exhibited thermal insulation approaching that of the PBI fabrics while the continuous filament fabrics displayed protection approaching that of cotton.

Of the staple fabrics evaluated, cotton exhibited the poorest thermal protection. The Nomex fabrics exhibited better thermal protection in comparison to the cotton fabric yet it offered less protection than the remaining fabrics. The Kynol fabrics exhibited good dimensional stability to flames and good thermal protection. Upon direct flame contact the fiber underwent thermal degradation to effect a resultant glassy carbon

residue on the fiber surface. This carbon cover acts as a thermal barrier and the remaining fiber mass still retains its shape. It is the fiber on fabric surface which by the nature of its thermal degradation process acts as a heat sink to absorb and dissipate the incoming heat while the remaining underlying fiber mass remains untouched. This provides the added protection as is evidenced by the Kynol fabrics. PBI provided superior thermal protection when compared to cotton and Nomex. The remaining staple fabrics were similar to PBI for thermal insulating purposes. It is believed that fabric No. 4 (F-fabric), which is made from continuous filament yarns, would have provided better protection had it been supplied in fabric made from staple yarns.

Fabric thickness and heat transmission through fabrics have been shown to be directly related to one another. The thickness necessary to provide three seconds protection time, as evidenced by the series of 2/1 twill weave fabrics (Tables III and V) should fall within the range of 12.7 to 18.0 mils. These are the corresponding thicknesses for the three second PAB times for the 1.0 and 1.3 cal/cm^2-sec exposure levels. This puts the fabric weight range from 3.4 to 6.2 oz/yd^2 for acceptable fabrics. The fabric chosen for actual use should be as close to the 18-mil fabric thickness as is possible without causing undue discomfort to the wearer because it retained too much warmth. Note that these figures are for the PBI fabrics and that similar figures could be derived for the remaining fabrics if provided in sufficient quantities. It cannot be stressed enough that the knit fabrics with their low weight and high fabric thickness (e.g., No. 27, PBI knit, 4.8 oz/yd^2, 28.5 mils) could supply a great deal of added protection as is evidenced by the PBI

knit fabrics 6.3 and 9/1 second PAB times (Table V). These tolerance times are based on the fiber remaining intact throughout the exposure time indicated.

Of the knit fabrics evaluated (Table II) only one form of knit construction (No. 13) qualified as a candidate flight suit material. It has a warp (tricot) knit construction which provides the necessary dimensional stability for flight suit fabrics. Its thickness and low fabric density combine to render it an effective thermal barrier. The tricot knit fabric (Table V, Log No. 13) has also demonstrated that a knit fabric can compete with woven fabrics for suit materials in terms of abrasion resistance and related mechanical properties. The remainder of the knit fabrics demonstrate the tremendous advantage that underwear fabrics can provide. In circumstances where the climate permits, long underwear can more than double the protection for a crewman while escaping from a burning aircraft.

Resultant temperature rises for all fabrics evaluated have been grouped together in Table V. Columns 4 and 5 depict the temperature rise in the NML skin simulant (ΔT_{css}) and the protection (time) against blistering (PAB) at an energy absorption level of 1.3 cal/cm^2-sec. This represents the protection, from a 1372°C flame, provided a substance of thermal and optical properties as is found in the simulated skin. Columns 6 and 7 provide the corresponding temperature rise (ΔT_{ss}/H) and protection time for an absorption level of 1.0 cal/cm^2-sec. The source of energy for the test was provided in the form of a rectangular pulse. The actual temperature range for a JP-4 fuel fire is 982 - 1204°C

and in the form of a wavering pulse. We can then assume that the conditions created by the test procedure are quite severe and that the actual protection time would be slightly better than is indicated by Column 5 and might then fall within the range of times indicated by Columns 5 and 7 for each fabric. One other point that should be noted is that since the conditions created are quite severe (fabric pulled tight against skin simulant and steady high temperature heat source) the protection time could extend beyond those times in Column 7 if the fabric did not shrink to the skin surface and the fabric remained intact to maintain that effective air barrier between the fabric and skin surface. Those fabrics supplied in sufficient quantities were evaluated further for resistance to flames (Table VI). As expected in the vertical flame test, cotton was totally consumed while the treated cotton was self extinguishing with a large evolution of smoke and considerable fabric damage. No flame time (i.e., flaming time recorded after 12 seconds exposure to flame source) was noted for any of the fabrics tested with the exception of the consumed cotton. Flame retardant cotton was charred and brittle with zero strength retention over the 4-inch char length. Nomex fabrics exhibited char lengths of 3.2 inches for fabric 6 and 3.4 inches for fabric 7, and glow times 13 and 15 seconds respectively. The remaining fabrics showed little or no effect from the vertical flame test.

The horizontal flame test utilizes a wider flame from a Fisher burner (1 1/2-inch diameter) than the Bunsen burner flame (3/8 inch diameter) used in the vertical flame resistance test. Because of the increased width of the flame, it is more intense and effects a larger

TABLE VI

FLAMMABILITY CHARACTERISTICS OF FABRICS

VERTICAL FLAME TEST NO. 5903			FABRICS		HORIZONTAL FLAME TEST
FLAME TIME (SEC)	GLOW TIME (SEC)	CHAR LENGTH (IN.)	FIBER TYPE	LOG NO.	COMMENTS
29	85	consumed	Cotton	1	Badly charred and stiffened
0	0	4.0	FR Cotton	2	Badly charred and brittle
0	0	0.0	Beta Glass	3	No change
0	2	0.0	F-Fabric	4	Slightly charred and stiff
0	3	1.3	Fi-Pro	30	No change
0	13	3.2	Nomex	6	Destroyed, supported combustion
0	15	3.4	Nomex	7	Destroyed, supported combustion
0	0	2.3	PBI	8	Slightly charred and stiff
0	0	0.6	PBI	9	No change
0	3	0.1	Kynol	10	Slightly charred and stiff
0	5	1.6	Durette-G	11	Slightly charred and stiff
0	3	1.3	Durette-B	12	No change
--	--	---	Nomex	13	Slightly charred and stiff
0	12	3.7	Nomex	26	Destroyed, supported combustion
0	0	2.4	PBI	27	Slightly stiff
--	--	---	PBI	35	Slightly stiff

surface area of the fabric upon exposure. The exposed fabric surfaces are shown in Figures 9, 10, and 11 and are designated by their log numbers. Both cotton fabrics were badly charred and stiffened (Table VI). The woven Nomex fabrics were all destroyed by the 3-second flame exposure and they supported combustion for a short time after removal of the flame source (1.5 sec). There was no further propagation of the flame along the Nomex fabric surfaces and they only continued to burn where they had collected into a charred mass on the edges of the burned section of the fabrics. Once again, as in the vertical flame resistance test, the remaining fabrics were only slightly damaged or were not affected at all. It was also found that by increasing the weight of the PBI fabrics from 3.7 oz/yd^2 (No. 8) to 4.7 oz/yd^2 (No. 35) the thermal stability of the fabric was enhanced. The knit construction of fabrics 13 (Nomex) and 27 (PBI) also helped to dissipate the heat more readily than the equivalent weight woven fabrics.

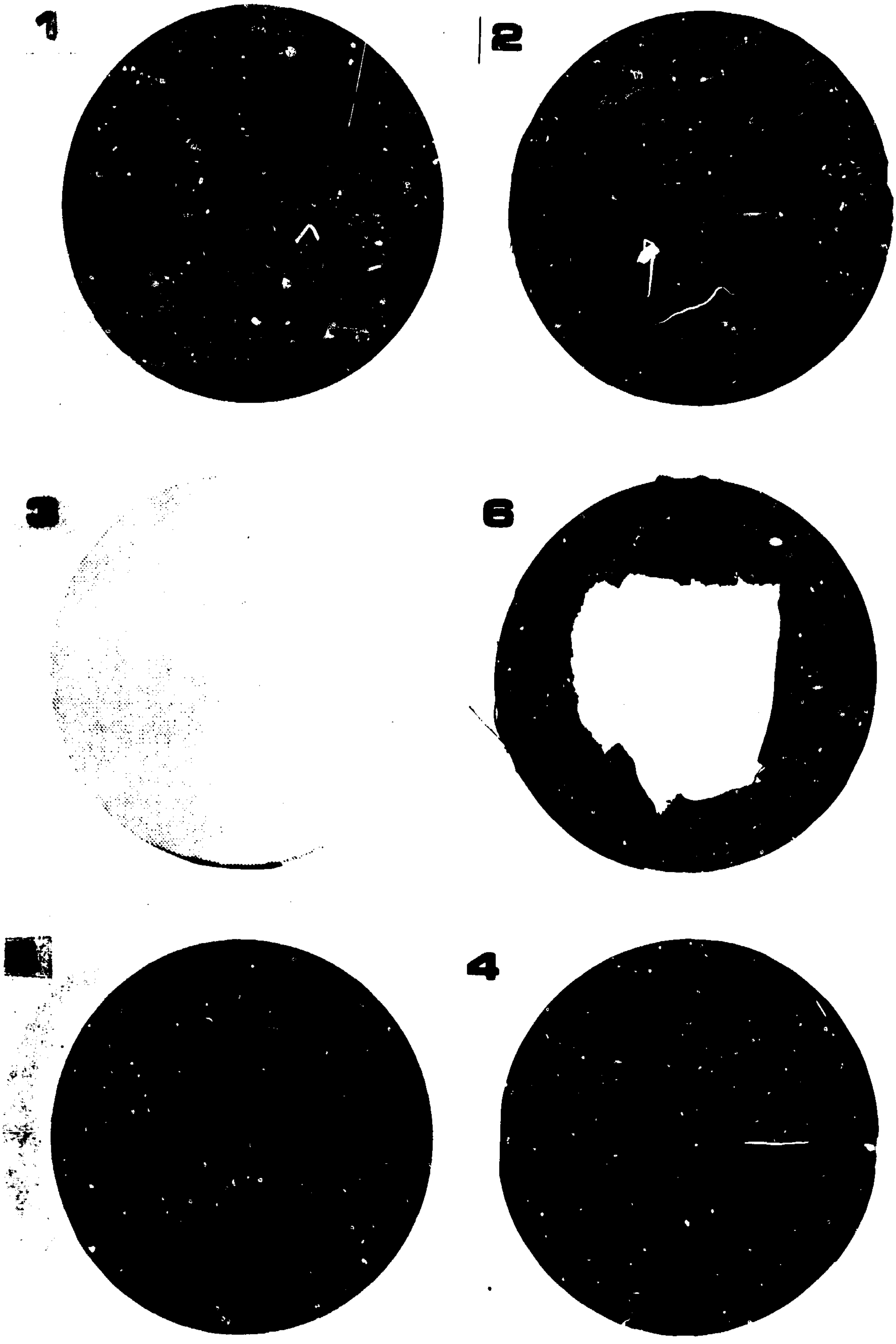


Figure 9. Horizontal Flame Test Results

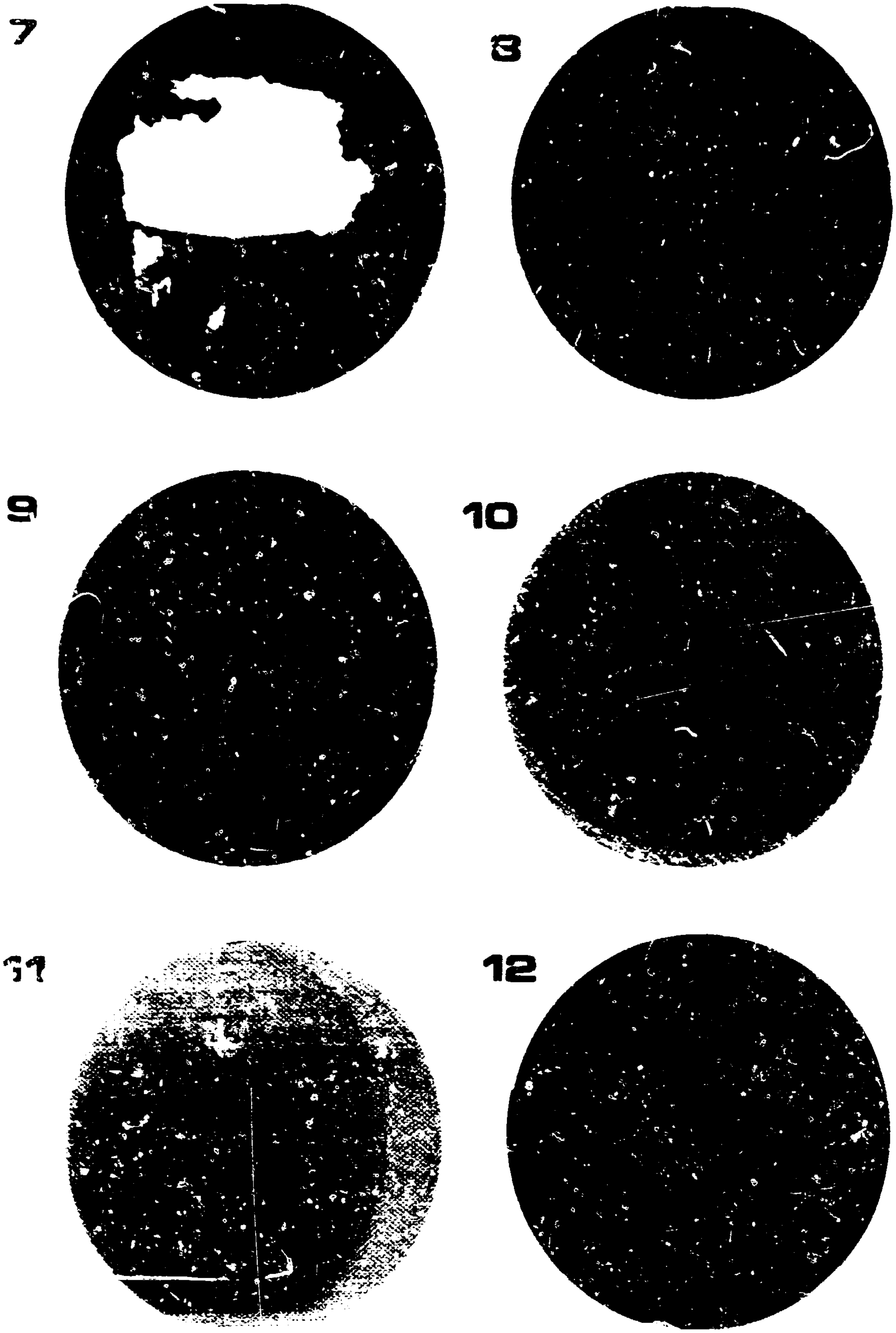


Figure 10. Horizontal Flame Test Results

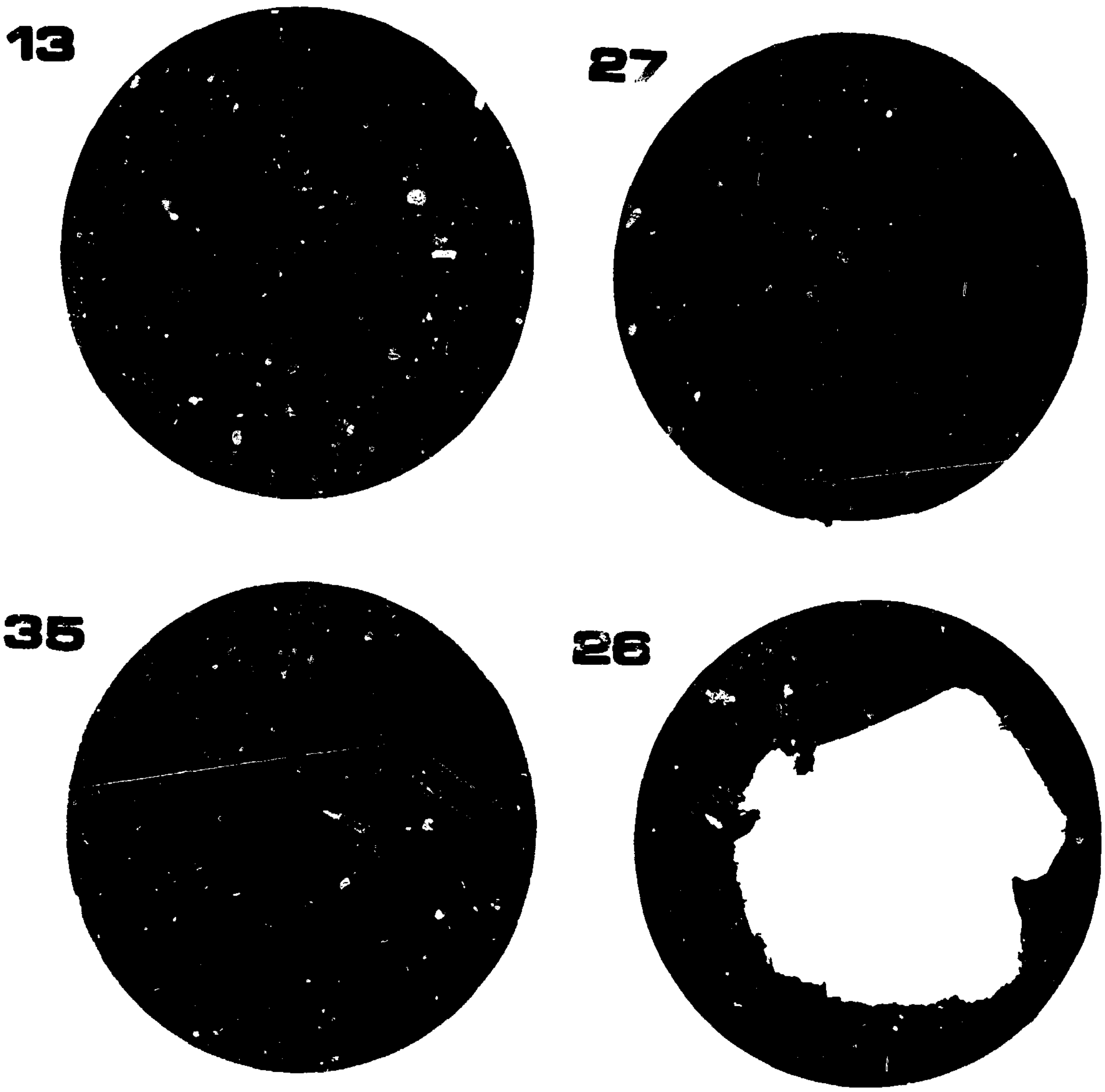


Figure 11. Horizontal Flame Test Results

SECTION VI

CONCLUSIONS

PBI is the only fabric that has shown the potential to provide the combination of comfort, nonflammability, thermal stability and mechanical characteristics for wear in the confined quarters of an aircraft cockpit.

PBI, Durette, Fi-Pro, F-Fabric and Kynol have all been shown to provide fabric nonflammability and fiber thermal stability for improved thermal protection over conventional fabrics.

PBI, Nomex, Durette, Fi-Pro, and F-Fabric have also demonstrated improved mechanical properties which should result in extended garment life when compared to U.S.A.F. cotton flight suits.

The following characteristics have been shown to retard heat transmission through fabrics upon direct flame contact:

1. Fiber thermal stability
2. Thickness
3. Weave or knit pattern
4. Air permeability
5. Bulk density

These characteristics can be effectively manipulated to provide the ultimate protection.

Knit fabrics can be constructed to provide superior thermal protection on a protection versus fabric weight basis. The thick yet low bulk density can cancel out the adverse effects of high air permeability generally found in knit fabrics.

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13. ABSTRACT

The need for nonflammable fibrous materials intended for incorporation into life support systems for aircrew protection from fires along with the state-of-the-art of such materials is discussed. Fabrics are evaluated on the basis of heat transmission from direct flame contact as well as for flammability. Five characteristics have been found to affect fabric heat transfer: fiber thermal stability, thickness, weave or knit pattern, air permeability and bulk density. PBI is the only fiber in woven form that has provided the combined thermal and comfort characteristics required for use in flight suits.

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Heat Transfer						
Thermal Protection						
Polybenzimidazole						
Nomex						
Kynol						
Durette						
Fi Pro						
F-Fabric						
TH PC Treate Cotton						